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# SPIRE - Spectral Infrared Rocket Experiment (Preliminary Results)

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11 April 1978

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This report has been reviewed by the ESD Information Office (OI) and is releasable to the National Technical Information Service (NTIS).

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FOR THE COMMANDER

John Howard

Chief Scientist

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On 28 Sept., 1977 at 1533 GMT, a Talos Castor rocket carrying the SPIRE payload was launched from the Poker Flat Research Range, Alaska. The objective of the SPIRE experiment, which was supported by the Defense Nuclear Agency, was to obtain infrared emission spectra of the earth's upper atmosphere in a limb-viewing geometry to test theoretical predictions of enhanced nuclear backgrounds. Two cryogenically cooled CVF spectrometers and a dual channel photometer were used to spatially and spectrally map the horizon from 5000 Å to 16.5 μm. All three sensors were telescoped with low scatter optics that resolved an 8-km footprint at the limb while rejecting competitive terrestrial and solar radiation. SPIRE successfully achieved all major objectives,


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making near simultaneous spectral measurements of both the sunlit and night earth limb in the SWIR and LWIR. Many of the atmosphere's infrared-active species were observed during some 12 separate elevation scans at different azimuth angles from the sun. These include OH, NO, $CO_2$, $H_2O$, $O_3$, and $HNO_3$.

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# Foreword

The High Altitude Effects Simulation (HAES) Program, sponsored by the Defense Nuclear Agency since early 1970, comprises several groupings of separate but interrelated technical activities; one of these groupings, ICECAP (Infrared Chemistry Experiments - Coordinated Auroral Program) has the objective of providing information essential to the development and validation of predictive computer codes designed for use with high priority DoD radar, communications, and optical systems.

Since the inception of the HAES Program, significant achievements and results have been described in the reports published by DNA, participating service laboratories, and supportive organizations. In order to provide greater visibility for such information and enhance its timely applications, significant reports published since early calendar 1974 have been identified with an assigned HAES serial number and the appropriate activity acronym (for example, ICECAP) as part of the report title. A complete and current bibliography of all HAES reports issued prior to and subsequent to HAES Report No. 1 is maintained and available on request from DASIAC, DoD Nuclear Information and Analysis Center, 816 State Street, Santa Barbara, California 93102, Telephone (805) 965-0551.

This report, the seventy-fifth in the HAES series, presents the first results of the SPIRE earth-limb experiment. Since data reduction and analysis are still in progress, the data herein must be considered preliminary. A representative sample of SWIR and LWIR data from 3 of the 12 earth-limb scans are shown, with emphasis on the sunlit/night comparisons examined to date.

# Preface

The success of the SPIRE experiment required the dedicated efforts of a large team of scientists, engineers, and technicians. The authors gratefully acknowledge the contributions of the following personnel and their organizations: Lynn Bates, Ed Vendell, David Morse, Larry Jensen, Val King, Dean Shaffer, and Don Rasmussen of Utah State University for the development, calibration, and operation of the three primary sensors; William Williamson of Honeywell Radiation Center who managed the fabrication and testing of the high rejection telescopes; Ed Allen, Steve Fisher, and Rick Park of Space Data Corporation for the integration, telemetry, and ranging support; Don Bradshaw and Glen True of Ball Brothers Corporation for the precise operation of the attitude control system; Tom Condron and Tony Austin of AFGL for the thorough calibration of the sensors; and Richard Hegblom and Carol Foley of Space Data Analysis Lab, Boston College, for their efficient processing of the data. Other significant contributions were made by: John Dulchinos, Henry Miranda, Carl Arcardo, and Rick Miranda of Epsilon, Inc.; Dr. Neal Brown, Eldon Thompson, Lou Baim, Henry Cole, and Dr. Tom Hallinan of the University of Alaska; Ed Butterfield of White Sands Missile Range; James C. Ulwick and Phillip Doyle of AFGL; and Herb Mitchell of RDA Associates. This experiment was funded by the Defense Nuclear Agency where the continued support of Dr. Carl Fitz, Dr. Gordon Soper, Major James Mayo, and Lt. Comdr. Chris Thomas has been vital and greatly appreciated. The editing and typing of the manuscript by Ms. Brenda Cerullo is gratefully acknowledged.

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# SPIRE—Spectral Infrared Rocket Experiment (Preliminary Results)

## 1. INTRODUCTION

Under the sponsorship of the Defense Nuclear Agency (DNA), the Optical Physics Division of AFGL has successfully conducted a rocket-borne, limb-viewing, infrared spectral experiment. The rocket payload, called SPIRE, was designed to test predictions of nuclear enhanced atmospheric backgrounds by measuring the natural sunlit atmosphere in a limb-viewing mode. Launched immediately before sunrise on 28 September 1977 from the University of Alaska's Poker Flat Research Range, SPIRE performed a wide ranging survey of both sunlit and nighttime horizon backgrounds. The primary payload instrumentation consisted of a short-wavelength liquid-nitrogen-cooled circular variable filter (CVF) spectrometer (1.4 to 4.5 $\mu$m), a long-wavelength liquid-helium-cooled CVF spectrometer (3.7 to 6.8 $\mu$m and 8.7 to 16.5 $\mu$m), and a two-channel photometer system with bands centered at 4977 Å and 6972 Å. These sensors were developed by the Electrodynamics Laboratories of Utah State University and equipped with special high off-axis rejection telescopes with 1/4 degree fields-of-view fabricated by the Honeywell Radiation Center. Two stellar aspect sensors and a low-light-level TV completed the instrument complement.

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This paper was presented in March 1978 at the DARPA sponsored SIXTH STRATEGIC SPACE SYMPOSIUM held at SRI, Menlo Park, Calif.

(Received for publication 10 April 1978)

A STRAP III programmable attitude control system maneuvered the SPIRE payload through 12 vertical spatial scans of the earth limb, as shown in Figure 1. The measurements are divided into three phases, with the first seven limb scans forming a tight pattern about the terminator. Here, at altitudes from 60 to 100 km, some of the more important changes in molecular emissions, which give rise to infrared backgrounds, occur. As SPIRE approached apogee, the eighth limb scan was made in the earth's shadow to provide a quiescent benchmark for the sunlit measurements. Following a long azimuth traverse back across the terminator, scans 9 through 12 examined the effect of several solar incidence angles on both high altitude emissions and lower altitude infrared aerosol scattering.

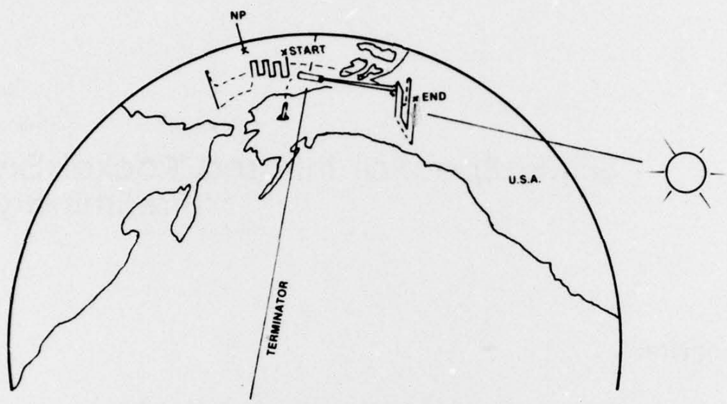


Figure 1. SPIRE Earth Limb Scan Profile

Excellent infrared and visible emission data were recovered from the measurement systems on all data channels throughout the 12 limb scans. Our initial review of the results indicates there are over 500 usable infrared spectra on each CVF, plus continuous visible band photometric data on the sunlit limb scans. The primary nuclear background effects for which SPIRE was designed appear to have been measured for the first time. These are: (1) ozone chemiluminescence in the 10 $\mu$m region from the recombination $O + O_2 + M \rightarrow O_3^{\neq} + M$, and (2) $CO_2$ enhancements in various wavelength regions produced by such mechanisms as:

fluorescence, $h\nu + CO_2(000) \rightarrow CO_2(101,021) \rightarrow CO_2(100,020) + 4.3\ \mu m$

$\rightarrow CO_2(000) + 13.8,\ 15.0,\ 16.2\ \mu m$

and

$$\left.\begin{array}{ll} \text{fluorescence,} & h\nu + CO_2(000) \\ \text{vibraluminescence,} & N_2^{\neq} + CO_2(000) \end{array}\right\} CO_2(001) + M \rightarrow CO_2(020,100)$$

$\rightarrow CO_2(100,000) + 10.4,\ 4.26\ \mu m$

Results also show exoatmospheric molecular infrared emission spectra of the near earth limb from $CO_2$ resonant scattering at 4.3 and 15 μm, NO at 5.3 μm, $H_2O$ from 6.3 to 6.6 μm, $O_3$ at 9.6 μm, $HNO_3$ at 11.3 μm, and OH at 1.5 to 3.5 μm. Due to the large amount of spectral data obtained, data reduction is still in progress and only limb scans 4, 8, and 11 have been looked at in any detail. Selected results from these three scans are presented in this paper, with emphasis on the intensity of the natural horizon backgrounds in the SWIR and MWIR.

## 2. SPIRE INSTRUMENTATION PERFORMANCE

The SPIRE payload utilized three primary sensors. Two circular variable filter (CVF) spectrometers — the liquid-nitrogen-cooled NS-2 and the liquid-helium-cooled HS-2 cover the SWIR and LWIR, respectively, yielding two spectra every second. An uncooled dual-channel photometer (TPM-1) extended measurements into the visible to monitor aerosol scattering at 4977 Å and 6972 Å. All three instruments were coupled to high off-axis rejection telescopes and co-aligned to intercept a nominal 8-km footprint at the earth limb. Table 1 summarizes the chief instrument characteristics, which are more fully described in a previous paper by Nadile, et. al.[1] Instrument calibration and telescope cooling were maintained throughout the flight with off-axis rejection more than sufficient on all but the closest spatial scan to the sun.

Two star sensors and a TV camera were to provide redundant aspect information to accurately monitor payload orientation and, thus, determine the tangent height intercept of the sensor line of sight. Failure of the TV camera shortly after lift-off combined with insufficient baffling of the primary celestial aspect sensor has precluded a definitive aspect solution to date. The back-up stellar sensor, a five-slit photometer oriented to monitor the payload pitch plane, appears to have operated normally. However, the combination of five slits scanning a rich star field makes analysis of this data difficult without some a priori information.

Table 1. SPIRE Sensor Characteristics

| Parameter | HS-2 CVF | NS-2 CVF | TPM-1 |
|---|---|---|---|
| Wavelength Coverage (μm) | 3.7 - 6.6 and 8.7 - 16.5 | 1.43 - 4.51 | 0.4977 Å and 0.6972 Å |
| Spectral Resolution (μm) | 0.115 - 0.293 | 0.026 - 0.054 | 43 Å and 54 Å |
| Detector Type | Si:(As) | InSb | Photomultiplier |
| NESR (W $cm^{-2}sr^{-1}\mu m^{-1}$) | $1.9 \times 10^{-9}$ at 10 μm | $2.0 \times 10^{-8}$ at 3 μm | $3.5 \times 10^{-7}$ |
| Dynamic Range | $3 \times 10^4$ | $3 \times 10^4$ | $3 \times 10^5$ |
| Field of View (sr) | $1.2 \times 10^{-5}$ | $1.7 \times 10^{-5}$ | $1.3 \times 10^{-5}$ |
| Cryogen | LHe | $LN_2$ | None |

1. Nadile, R.M., Wheeler, N.B., Stair, A.T., Jr., Frodsham, D.G., and Wyatt, C.L. (1977) SPIRE - Spectral Infra Red Experiment, SPIE Proceedings, Volume 124, Modern Utilization of Infrared Technology III, August.

While the back-up stellar sensor still holds some promise for a more accurate aspect solution, the data presented herein are assigned tangent heights based on known features in the infrared data itself. That this is at all feasible is in large part due to the outstanding performance of the Ball Brothers, Inc. attitude control system, and to the precise alignment of the telescoped sensors by the payload integrator, Space Data Corporation. Though no substitute for a unique stellar aspect solution, a reasonable aspect solution utilizing the known altitude of hydroxyl emission in the airglow layer is detailed in the following section.

## 3. AIRGLOW DATA

The most consistent layered data in the short-wavelength spectrometer are emissions from nighttime (OH) in the overtone spectral region from 1.4 to 2.3 μm and in the fundamental at 2.92 μm. Since housekeeping data show the ACS scan rate to be constant at 1/2 degree per second, a relative tangent height profile of these emissions can be generated for each limb scan. Because the airglow is a relatively thin, well defined layer,[2] a good estimate of its tangent height can be made. This was done rigorously for scans 4 and 8, using OH overtone zenith rocket data extrapolated to the SPIRE viewing geometry.[3] A good fit was obtained on both the terminator and night scans, using an 84 km tangent height for the OH overtone maximum. This choice of altitude is, of necessity, an 'a priori' assumption for the specific time and location of the SPIRE measurements. It is estimated that this method of converting vertical to limb geometry is accurate to within 5 km at airglow altitudes, with some further degradation at other tangent heights due to small non-linearities in the scan rate.

Airglow emissions are prominent throughout the terminator and night SWIR spectral data. Two examples of the hydroxyl fundamental emission (2.9 μm) are shown in Figure 2. The twilight data from limb scan 4 is representative in that all airglow terminator data are more intense than the single nighttime sample. Spatial patchiness and regular diurnal variations in hydroxyl have been observed,[4] which could account for the observed differential. The OH radiance profiles are characterized by a sharp upper boundary, which defines the top of the layer, and a long tail to lower altitudes caused by the limb-viewing geometry. Evidence of a secondary peak at approximately 65 km is apparent in almost all the OH profiles examined to date. This feature would be very difficult to detect with a vertical sounding rocket, since it would be masked by the more intense emission at higher altitudes.

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2. Rogers, J.W., Murphy, R.E., Stair, A.T., Jr., Ulwick, J.C., Baker, K.D., and Jensen, L.L. (1973) Rocket-borne radiometric measurements of OH in the auroral zone, J. Geophys. Res. **78** (No. 30): 7023-31.

3. Grieder, W.F., Baker, K.D., Stair, A.T., Jr., and Ulwick, J.C. (1976) Rocket Measurements of OH Emission Profiles in the 1.56 and 1.99 μm Bands, AFCRL-TR-76-0057, ERP No. 550, HAES Report No. 38.

4. Huppi, R.J., and Baker, D.J. (1976) Intensity Variations of Atmospheric Hydroxyl Emissions, AFCRL-TR-76-0032.

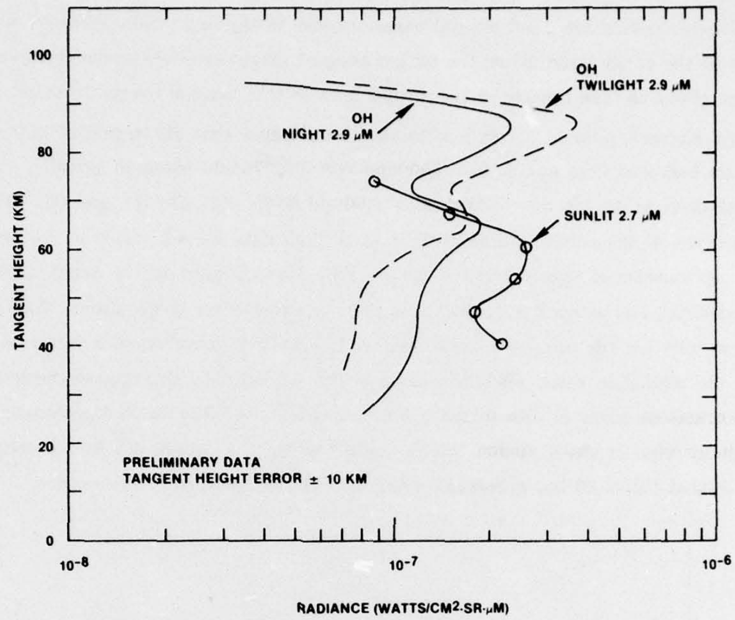


Figure 2. Horizon Backgrounds in the 2.5 - 3.0 μm Region

Also shown on Figure 2 is an unknown emitter at 2.7 μm seen only during the sunlit-limb scans. This is tentatively attributed to fluorescence of $CO_2$ and or $H_2O$ as a result of solar radiation absorption. It should be noted here that the day side tangent heights are less accurately known. Though some day side airglow ($\Delta v = 2$) was detected in limb scan 11, the signal to noise was insufficient to establish a definitive tangent height reference. For this purpose, a "knee" in the $CO_2$ $\nu_3$ (4.3 μm) radiance profile was used that was common to both the day and night data.

## 4. $CO_2$ DATA

The MWIR data is dominated by 4.3 μm emission in the $CO_2$ ($\nu_3$) band below 100 km. Radiance profiles of the spectral peak from scans 4 and 8 are almost identical, and are believed to represent the nominal quiescent level due to resonant scattering of earthshine. The night scan is plotted in Figure 3 using tangent heights based on the airglow criteria described in Section 3. A small discontinuity in the normal roll-off with altitude is observed between 80 and 95 km, particularly in the terminator profile (not shown). This is tentatively attributed[5] to the transfer of energy from vibrationally excited OH in the airglow: $OH^{\neq} \xrightarrow{VV} N_2 \xrightarrow{VV} CO_2$ ($\nu_3$). The effect is somewhat masked in limb scan 8

5. Kumer, J.B., Stair, A.T., Jr., Wheeler, N.B., Baker, K.D., Baker, D.J. (1978) Evidence for hydroxyl vibrational transfer of nitrogen to the $\nu_3$ band of $CO_2$ producing a 4.3 μm airglow layer, Accepted for publication, J. Geophys. Res.

by what is believed to be a low level auroral enhancement[6] in the night data above 70 km. The optical thickness of the entire band below the 50 km tangent height is obvious due to the constant radiance at lower altitudes. The centers of the strong lines in this band are actually thick to 90 km.

James and Kumer[7], pointed out in a 1973 theoretical paper that absorption of radiation in the 2.7 and 2.77 $\mu$m bands of $CO_2$ due to 000→101 and 000→021 should result in a major source of fluorescent emissions at 4.3 $\mu$m due to the decay of these levels via 101→100 and 021→020. Figure 3 shows a comparison of the sunlit to dark SPIRE earth limb data for 4.3 $\mu$m; it is the first experimental confirmation of this hypothesis for the limb view. Subject to the uncertainties in tangent altitudes, the sun-pumped fluorescence is perhaps even larger in magnitude than predicted. For example, at ~80 km the measured limb radiance is ~$5 \times 10^{-6}$ W/cm$^2$sr$\mu$m, a factor of about 40 brighter than the nighttime value. Certain aspects of the 4.3 $\mu$m data also appear consistent with previous theoretical estimates of James and Kumer[7] and Degges.[8] The sunlit fluorescence data has a marked change in slope at about 80 km, which would confirm the James and Kumer calculations (their Figure 5) that below 80 km quenching dominates vibrational quanta destruction.

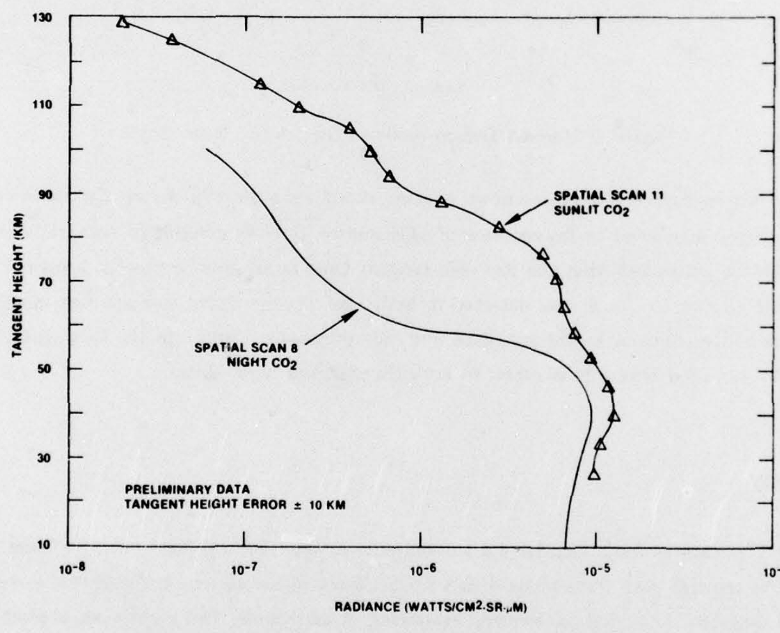


Figure 3. $CO_2$ (4.3 $\mu$m) Sunlit-Pumped Fluorescence

6. Stair, A.T., Jr., Ulwick, J.C., Baker, K.D., and Baker, D.J. (1975) Rocket-borne Observations of atmospheric infrared emissions in the Auroral Region in Atmospheres of Earth and the Planets, pp. 335-346, B.M. McCormac (editor), D. Reidl Publishing Company, Dordrecht-Holland.

7. James, T.C., and Kumer, J.B. (1973) Fluorescence of $CO_2$ near 4.3 microns: application to daytime limb radiance calculations, J. Geophys. Res., **78** (No. 34):8320-29.

8. Degges, T.C. (1974) A High Altitude Infrared Radiance Model, AFCRL-TR-74-0606.

## 5. LWIR DATA

A sample spectrum obtained with the liquid-helium-cooled, long-wavelength CVF is shown in Figure 4. The estimated tangent height is 60 km with a possible error of ± 10 km. This spectrum was taken during limb scan number 4 which includes a partially sunlit atmosphere. The data shown are representative of the signal-to-noise and spectral resolution of the HS-2 spectrometer. Until the correct tangent heights and solar angles are established, a detailed spectral analysis will not be undertaken; however, a few comments on the spectra may be useful.

The data is shown in two spectral intervals, 4 to 7 $\mu m$ and 9 to 17 $\mu m$. The spectral resolution element of the spectrometer consisted of two separate wedge filters with a dc reset optical mask separating them[9]. Since the circular interference filter can only cover one octave, the region between 7 and 9 $\mu m$ was not covered to obtain data on the 4.3 and 15 $\mu m$ bands of $CO_2$. At 4.3 $\mu m$ is the strong ($1.6 \times 10^{-6}$ w/cm$^2$sr$\mu$m) and well-resolved $\nu_3$ band of $CO_2$. The spectral feature at 4.8 $\mu m$ is presumably due to contributions from $CO_2$ (111→000) and/or $O_3$(101→000). These bands were resolved and observed to have approximately equal radiance levels in a vertical viewing measurement from our KC-135, Serial Number 3120, flying at 12 km (Huppi, et. al., Ref. 10). The next maximum occurs at about 5.25 $\mu m$ and is the R branch of the 1-0 fundamental band of NO. The P branch is largely washed out by the $\nu_3$ band of $H_2O$ whose center is the minimum seen at 6.3 $\mu m$. The identification of the 5.3 fundamental of NO is unambiguous due to data at higher tangent heights where there is no observable $H_2O$ emission (above ~90 km), and the 5.3 band (with clearly resolved P and R bands of the 1-0 transition) is the dominant spectral feature in this wavelength region. We think that the spectrum from 6 to 7 $\mu m$ is primarily due to the strong $\nu_3$ fundamental of $H_2O$.

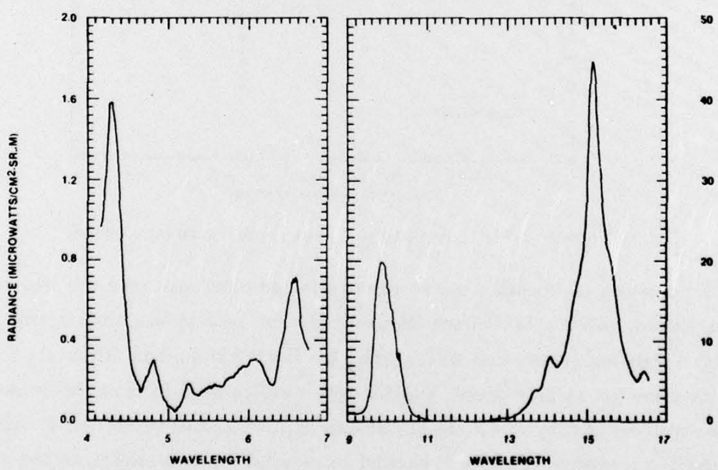


Figure 4. HS-2 Spectra, Limb Scan 4, 60 km Tangent Height ± 10 km

9. Wyatt, C.L. (1975) Infrared spectrometer; liquid-helium-cooled rocket-borne circular-variable filter, Appl. Opt., 14: 3086-91.
10. Huppi, E.R., Rogers, J.W., and Stair, A.T., Jr. (1974) Aircraft observations of the infrared emission of the atmosphere in the 700-2800 cm$^{-1}$ region, Appl. Opt., 13: 1466-76.

In the long wavelength half of the spectrum (9–17 μm), the feature peaking near 10 μm is due to the $\nu_3$ fundamental of $O_3$. The wide extent of the band with measurable radiances to nearly 11 μm means that more than just the 001→000 transition is involved. Other spectra with different sunlit conditions and from higher tangent heights show a more marked broadening at the longer wavelengths. This is evidence for either ozone chemiluminescence from the three body recombination reaction, which has an exothermicity of about 1 eV, and/or $CO_2$ fluorescence from the solar-pumped 001 state radiatiating to the 100 state (10.4 μm). The intense spectral feature at 15 μm is due to the $\nu_2$ fundamental of $CO_2$. The spectral resolution was just sufficient to resolve the Q branches of some of the other transitions such as 100→010, 13.8 μm and 020→010, 16.2 μm.

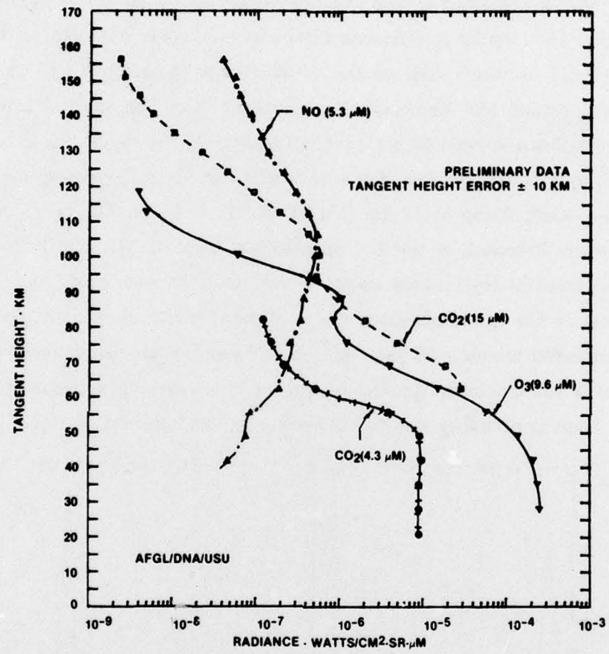


Figure 5. SPIRE Nighttime Earth Limb Emission Profiles

In Figure 5 we present a smoothed set of curves through data points for the peak night radiance values vs altitude. All but two of the observed spectral features measured by the HS-2 spectrometer are shown. Missing species and wavelengths are $H_2O$ (6.3 μm) and $HNO_3$ (11.3 μm), missing simply because they are yet to be reduced. The discussion will proceed in order of increasing wavelengths. The $\nu_3$ band of $CO_2$ at 4.3 μm has already been discussed in Section 4. The emission at 5.3 μm due to the 1–0 transition of NO can be seen to be a broad layer peaked around 110 km. For a non-auroral case, which we think this is, the populating mechanism for the high altitude radiation is

assumed to be O atom interchange NO + O′ → NO′ + O (Degges, Ref. 11). This layer was also observed during the ICECAP vertical soundings[6] and has been reported by Russian investigators for a limb-viewing satellite[12]. The Russian data for this spectral feature in the sunlit case are nearly 2 orders of magnitude larger than shown here, and the layer is observed to be at much higher altitudes. This reaction has an appreciable temperature dependence so that day/night differences are anticipated, but not to this degree. The 9.6 $\mu$m emission due to the $\nu_3$ band of $O_3$ is observed from 25 km to 120 km. The layer around 90 km is very marked in this data. There is an increase in ozone concentration at these altitudes, which accounts for this effect. More unexpected is a 'layer' in the limb radiance of the 15 $\mu$m $CO_2$ $\nu_2$ emission. An effect like this was observed in a 1974 vertical viewing CVF flight but was not evident in the 1973 data[13]. A much more complete discussion of the excitation and quenching mechanisms affecting these radiators is given by Degges[6]. Other major contributions to these models are due to James and Kumer[7] and Kumer, et. al.[5]

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3. Grieder, W.F., Baker, K.D., Stair, A.T., Jr., and Ulwick, J.C. (1976) Rocket Measurements of OH Emission Profiles in the 1.56 and 1.99 μm Bands, AFCRL-TR-76-0057, ERP No. 550, HAES Report No. 38.

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